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BIOPHYSICAL CHARACTERISTICS OF CHEMICAL PROTECTIVE ENSEMBLES WITH AND WITHOUT BODY ARMOR

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United States Army
Medical Research & Materiel Command

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BIOPHYSICAL CHARACTERISTICS OF CHEMICAL PROTECTIVE ENSEMBLES WITH AND WITHOUT BODY ARMOR

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14. ABSTRACT
Chemical, Biological, Radiological, and Nuclear (CBRN) personal protective equipment (PPE) ensembles are designed to both provide individual protection from CBRN threats, and allow the individual's sufficient freedom of motion to complete mission-essential tasks. Encapsulation in PPE significantly increases the risk of heat strain. Heat strain is a particularly serious risk for CBRN missions where the individual's ability to dissipate excess metabolic heat is significantly reduced. The Department of Defense (DoD) has been tasked with improving the current issue PPE, with one of the goals being to optimize the balance between CBRN protection and thermal burden. Methods: A sweating thermal manikin in a climate-controlled wind tunnel was used to measure the thermal insulation, vapor permeability, and wind velocity effects for each ensemble. This report provides quantitative biophysical assessments of 14 CBRN ensembles, including candidate prototypes and current issue suits, and ranks each by level of associated thermal burden. From this assessment a tradeoff analysis between CBRN protection and thermal strain can be conducted.

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ACRONYMS AND ABBREVIATIONS

A	surface area in m^2
ASTM	American Society for Testing and Materials
C	convection
CBRN	Chemical, Biological, Radiological, and Nuclear
Clo	unit of thermal insulation
Cyre	Crye Precision brand body armor (http://www.cryeprecision.com)
DoD	Department of Defense
E	evaporation
FRACU	Flame Resistant Army Combat Uniform
IFS	Integrated Footwear System
i_m	vapor permeability index
I_T	total thermal resistance
JB1GU	JSLIST Block 1 Glove Upgrade
JSLIST	Joint Service Lightweight Integrated Suit Technology
K	conduction
M	metabolic rate
MICH	Modular Integrated Communications Helmet
MTNW	Measurement Technologies Northwest (http://www.mtnw-usa.com/)
P_a	vapor pressure in Pascal units
P_{sat}	vapor pressure at the surface in Pascal units
Q	power input (in Watts)
R	radiation
R_{ct}	thermal resistance
R_{et}	evaporative resistance
S	heat storage
Std	standard
T_a	air temperature
T_s	surface or skin temperature
USCG AP PPE	US Coast Guard All Purpose Personal Protective Equipment suit
V	wind velocity
V^g	wind velocity coefficient
W	work rate

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EXECUTIVE SUMMARY

Chemical, Biological, Radiological, and Nuclear (CBRN) personal protective equipment (PPE) ensembles are designed to both provide individual protection from CBRN threats, and allow the individual's sufficient freedom of motion to complete mission-essential tasks. Encapsulation in PPE is not just encumbering but also significantly increases the risk of heat strain. Heat strain is a particularly serious risk for CBRN missions where the individual's ability to dissipate excess metabolic heat is significantly reduced.

The Department of Defense (DoD) has been tasked with improving the current issue PPE, with one of the goals being to optimize the balance between CBRN protection and thermal burden. Methods: A sweating thermal manikin in a climate-controlled wind tunnel was used to measure the thermal insulation, vapor permeability, and wind velocity effects for each ensemble. This report provides quantitative biophysical assessments of 14 CBRN ensembles, including candidate prototypes and current issue suits, and ranks each by level of associated thermal burden. From this assessment a tradeoff analysis between CBRN protection and thermal strain can be conducted.

INTRODUCTION

Chemical, Biological, Radiological, and Nuclear (CBRN) personal protective equipment (PPE) ensembles are an essential element of military operational equipment. These ensembles are designed to provide individual protection from CBRN threats, while minimizing the hobbling and encumbrance effects allowing Warfighters sufficient agility and mobility to complete mission-essential tasks. Nevertheless, the bulk, weight, and encapsulation associated with these protective ensembles compromises mobility, agility, situational awareness, and thermoregulation.

Thermal strain management during military training and operations is an important issue for our modern day Warfighters. The U.S. Armed Forces faces significant issues associated with heat illness and heat injuries during training. During 2013, the Armed Forces Health Surveillance Center (AFHSC) reported 1.44 heat injuries per 1,000 per year (n = 2,025); heat strokes specifically being 0.23 per 1,000 per year (n = 324) in non-deployed stations. The AFHSC also reported data from 2009-2013, for service members deployed to Iraq/Afghanistan, heat injuries totally 909, 58 of these being heat stroke [1]. While these incidences are relatively high across all types of training and operations, wearing CBRN ensembles impose an even greater risk of heat illness or injury by impeding the individual's ability to thermoregulate [2].

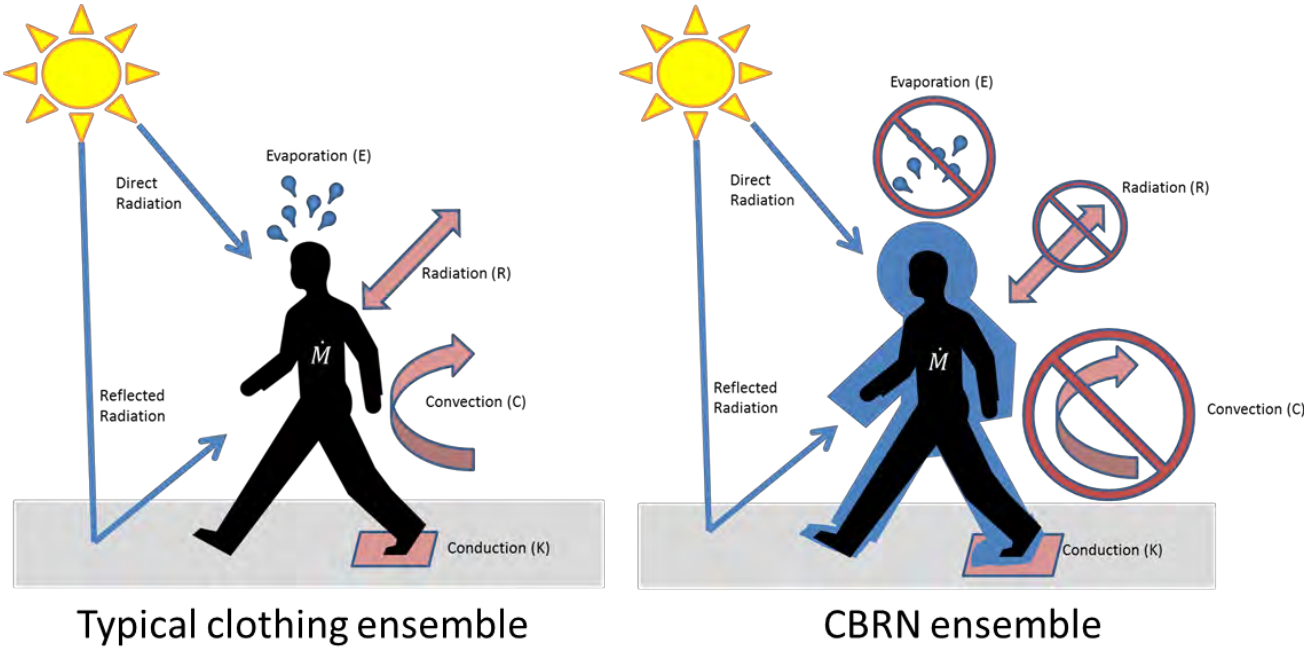
The human body's thermophysiological mechanisms normally maintain thermal homeostasis by generating or dissipating heat. As homeotherms, metabolic energy production ($\dot{M}$) in humans is a natural process, where ~20% of this energy results in useful mechanical work and ~80% goes to production of heat. Thermal balance is needed to maintain normal core body temperature via heat dissipation to the four pathways of heat exchange, radiation (R), convection (C), conduction (K), and evaporation (E), as:

$$S = M \pm W \pm R \pm C \pm K - E \; [\mathrm{W/m^2}]$$

where *S* is heat storage; *M* is metabolic rate; and *W* is work rate. Radiation is heat that is transferred via electromagnetic waves (e.g., solar or infrared radiation). Convection is heat transfer with fluid contact (e.g., air or water). Conduction is heat transfer from direct contact with a solid object (e.g., touching a cold surface). Evaporation is heat loss to the environment involving phase changes of water from liquid to vapor, typically as sweat and respiratory evaporative water loss.

CBRN protective ensembles impede heat dissipation, primarily by impeding cutaneous evaporative heat loss. By design, CBRN protective ensembles decrease the ability for CBRN threats to enter the suit and affect the human; however, this protection drastically reduces evaporative cooling and other routes of heat dissipation (i.e., if nothing gets in, nothing gets out). From a heat balance perspective, for individuals wearing CBRN ensembles, R, C, and E are either virtually eliminated or significantly reduced, thus compromising the individual's ability to dissipate excess metabolic heat and maintain thermal homeostasis (Figure 1).

Figure 1. Heat exchange in typical clothing ensembles compared to personal protective ensembles where routes of heat loss are restricted



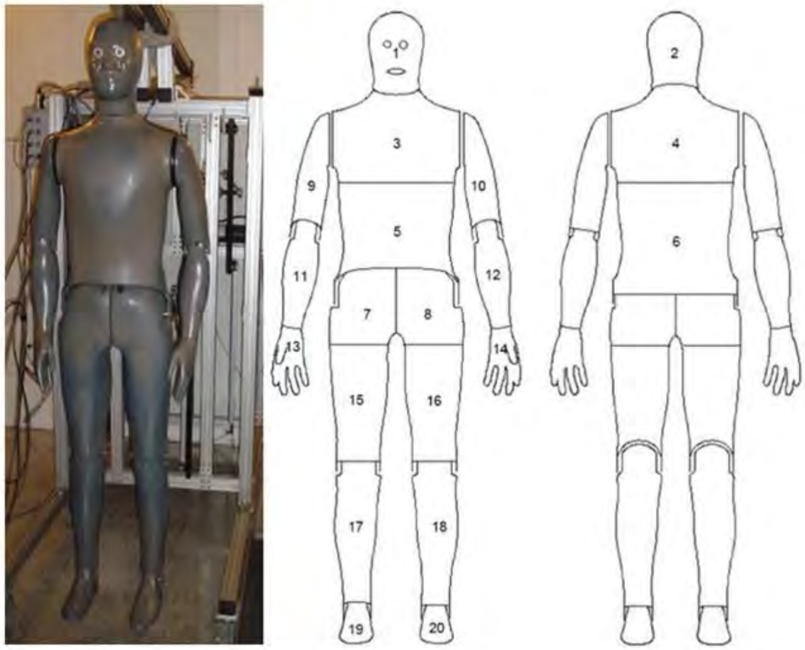
Recognizing the importance of reducing heat strain commonly experienced while wearing CBRN ensembles, a joint effort has been initiated within the Department of Defense (DoD) to improve the thermal characteristics of the current issue PPE. The goal is to optimize the balance between CBRN protection and heat strain.

This report provides quantitative biophysical assessments of some of these candidate protective ensembles to allow data-driven decisions with respect to tradeoffs between CBRN protection and thermal burden. Standardized test methods of ensemble biophysical characteristics, specifically thermal resistance and evaporative resistance, provide quantitative values for comparison.

METHODS

The biophysical characteristics of 14 CBRN ensembles were assessed using a sweating thermal manikin (Newton 20 zone, Measurement Technologies Northwest, Seattle, WA http://www.mtnw-usa.com/) (Figure 1), located in an environmentally controlled wind tunnel.

Figure 2. Thermal sweating manikin (20 zone Newton, Measurement Technologies Northwest)



Ensembles

Eight ensembles configurations with body armor and helmets, including three prototype ensembles (CB-BA-1 thru CB-BA-3) and four existing ensembles (CB-BA-4 thru CB-BA-8), and six configurations with no body armor or helmets (prototypes CB-1 thru CB-3 and baselines CB-4 thru CB-6) were tested. A full description of each of the test configurations and an associated photograph figure number can be seen in Appendix A.

Biophysical Assessments

Two fundamental parameters were used to describe the biophysical properties of these ensembles, thermal resistance (R_{ct}) and evaporative resistance (R_{et}). Thermal resistance is the measure of dry sensible heat transfer from the body into the environment, mainly from convection, described as:

$$R_{ct} = \frac{(T_s - T_a)}{Q/A} \, [\mathrm{m^2K/W}]$$

where T_s is surface temperature and T_a is the air temperature, both in °C or °K. Q is power input (in Watts) to maintain the surface (skin) temperature (T_s) of the manikin at a given set point; A is the surface area of the measurement in m^2.

Evaporative resistance is the measure of heat loss from the body in isothermal conditions ($T_s \approx T_a$), described as:

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}\,[\mathrm{m^2Pa/W}]$$

where P_{sat} is vapor pressure in Pascal units at the surface of the manikin (assumed to be fully saturated), and P_a is vapor pressure, in pascals, of the chamber environment.

Each ensemble was tested using chamber conditions from the American Society for Testing and Materials (ASTM) standards for assessing R_{ct} (ASTM F1291-10) and R_{et} (ASTM F2370-10) [3, 4] (Table 1).

Table 1. American Society for Testing and Materials (ASTM) standard chamber and manikin conditions for testing thermal (R_{ct}) and evaporative (R_{et}) resistance

Variable (units)	**Skin / surface temperature (T_s, °C)**	**Ambient temperature (T_a, °C)**	**Relative humidity (RH, %)**	**Wind velocity (V, ms^{-1})**	**Manikin surface saturation (%)**
R_{ct} (m^{2}K/W)	35	20	50	0.4	0
R_{et} (m^{2}Pa/W)	35	35	40	0.4	100

When testing R_{ct}, the major element being considered is dry sensible heat transfer from manikin to the chamber environment. Per ASTM standards, a temperature gradient of at least 15 °C between the manikin surface and the environment is needed. During assessment of R_{et}, the major element considered is insensible evaporative heat loss; when manikin T_s and ambient T_a are equal, the measured heat loss is due to evaporation.

The total thermal resistance (I_T) of an ensemble is the total measure of R_{ct} including all boundary air layers [5]. This measure of insulation is typically expressed in units of clo; where 1 clo = 6.45 · I_T [6]. The ensemble R_{et} is typically converted into a vapor permeability index (i_m) [7], a non-dimensional measure of water vapor resistance defined as:

$$i_m = \frac{60.6515\,\frac{Pa}{°C}\,\cdot\,R_{ct}}{R_{et}}$$

The i_m describes a material's range of permeability from 0 (completely impermeable) to 1 (completely permeable). From a practical perspective, achieving this theoretical value of 1.0 is unlikely given that measured open air values in environmental chambers range between 0.5 – 0.6. For all practical purposes a value of 0.6 represents a baseline value for a completely permeable ensemble. However, i_m values of 0 are possible in highly encapsulating ensembles such as explosive ordnance disposal (EOD) suits [8]. A ratio (i_m / clo) can be used to describe an ensemble's evaporative potential for any environment [9].

Wind Velocity Coefficient Assessments

Measures of R_{ct} and R_{et} were assessed for each ensemble under ASTM chamber conditions (Table 1). These tests were repeated within the same environmental conditions at increased wind velocities (V) in order to determine the effects of wind and to allow for modeling varied environments. Testing was conducted for both conditions (R_{ct} and R_{et}) at three different V settings. Wind velocities conditions used for each ensemble for R_{ct}: level 1: 0.52 ± 0.02, level 2: 1.43 ± 0.02, and level 3: 2.31 ± 0.04; and for R_{et}: level 1: 0.51 ± 0.02, level 2: 1.44 ± 0.03, and level 3: 2.30 ± 0.04 (ms^{-1}, mean ± SD). The additional two tests were used to establish wind velocity coefficients specific to each ensemble [10].

Each ensemble's measured values, converted to units of clo and index values of i_m, were aligned with their corresponding V, and a power regression line was calculated. This regression line was used to determine the wind velocity coefficient (V^g) for each ensemble, allowing clo, i_m, and i_m/clo values to be calculated at various values.

RESULTS

Biophysical Results

Testing results in Figures 3a-4c and Tables 2a-3c show the measured differences among the ensembles. Graphical representations of the clo, i_m, and i_m/clo for the eight CBRN ensembles with body armor are shown in Figures 3a, 3b, and 3c; while the corresponding data is presented in Tables 2a, 2b, and 2c. In Figure 3a differences in clo can be seen, including a significantly higher clo for CB-BA-8, which indicates a greater dry thermal insulation and thermal burden. Figure 3b shows differences in i_m, where higher values indicate increased ability for evaporative heat loss through the ensemble, where CB-BA-2 performs best in this regard. Notably, Figure 3c shows the i_m/clo, where higher values indicate better performing ensembles. This value for CB-BA-2 exceeds that of the other ensembles indicating that it has a greater evaporative potential and imposes lower thermal burden.

Graphical representations of the clo, i_m, and i_m/clo for the six CBRN ensembles without body armor are shown in Figures 4a, 4b, and 4c; while the corresponding data is shown in Tables 3a, 3b, and 3c. As described above for the ensembles with body armor, we see the optimal performing ensembles in these figures. Figure 4a shows a

significantly lower clo in CB-1, indicating lower thermal insulation and burden. Figure 4b shows a significantly lower i_m in CB-4, indicating a reduced ability for evaporative heat loss and an increased likelihood of thermal strain. Figure 4c shows a close comparison to CB-1 and CB-2 as the higher performing ensembles.

Figure 3a. Total thermal resistance (I_T, clo) by wind velocity (*V*) for eight ensembles with body armor and helmet

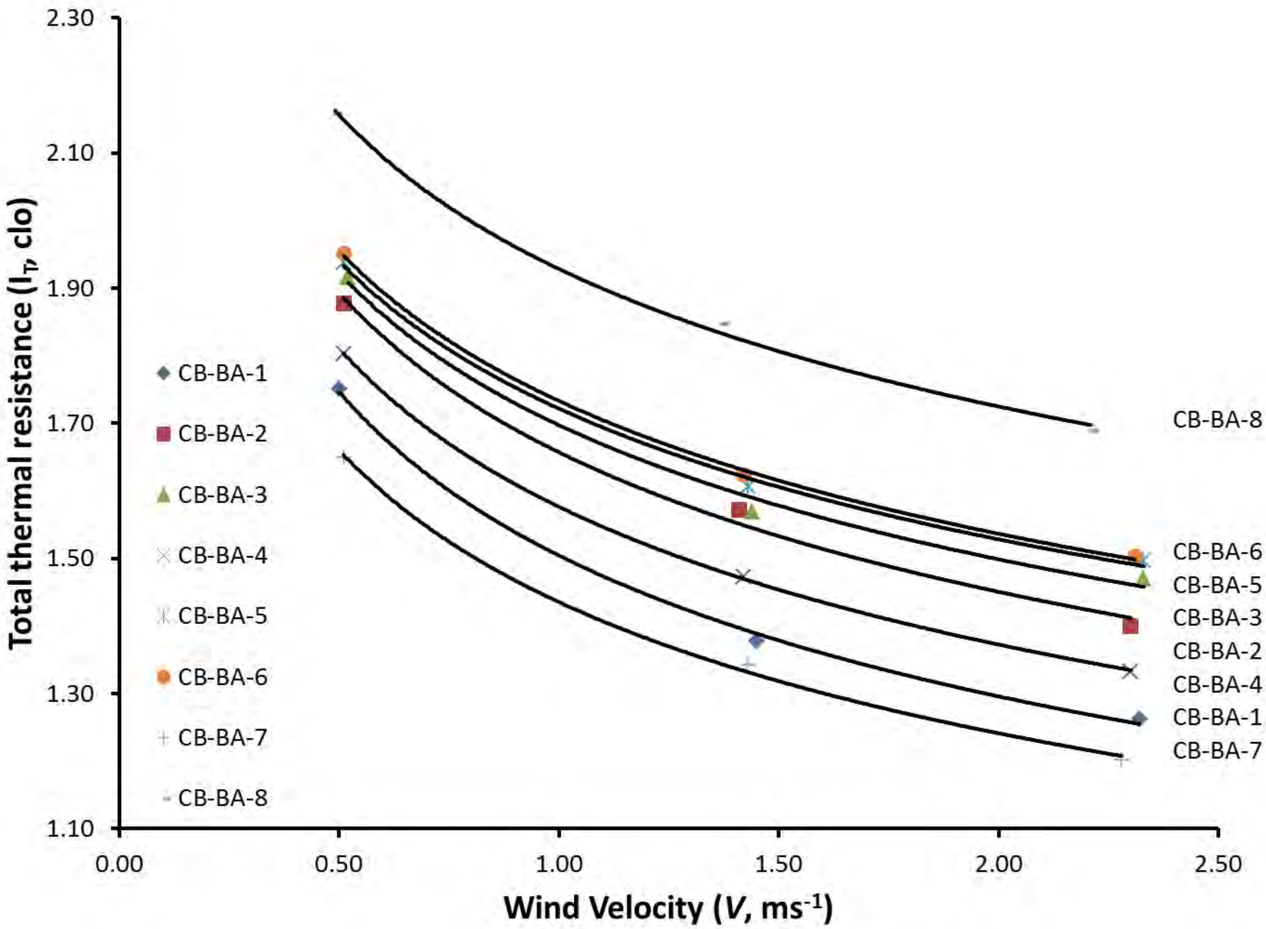


Table 2a. Total thermal resistances (I_T, clo) by wind velocity (*V*) for eight ensembles with body armor and helmet and associated wind velocity coefficient (V^g)

Ensemble	**clo: 1** **V: 0.52 ms^{-1}**	**clo: 2** **V: 1.43 ms^{-1}**	**clo: 3** **V: 2.31 ms^{-1}**	**cloV^g**
CB-BA-1	1.75	1.38	1.26	-0.22
CB-BA-2	1.88	1.57	1.40	-0.19
CB-BA-3	1.92	1.57	1.47	-0.18
CB-BA-4	1.80	1.47	1.33	-0.20
CB-BA-5	1.94	1.61	1.50	-0.17
CB-BA-6	1.95	1.62	1.50	-0.17
CB-BA-7	1.65	1.34	1.20	-0.21
CB-BA-8	2.16	1.85	1.69	-0.16

Figure 3b. Vapor permeability index (i_m) by wind velocity (*V)* for eight ensembles with body armor and helmet

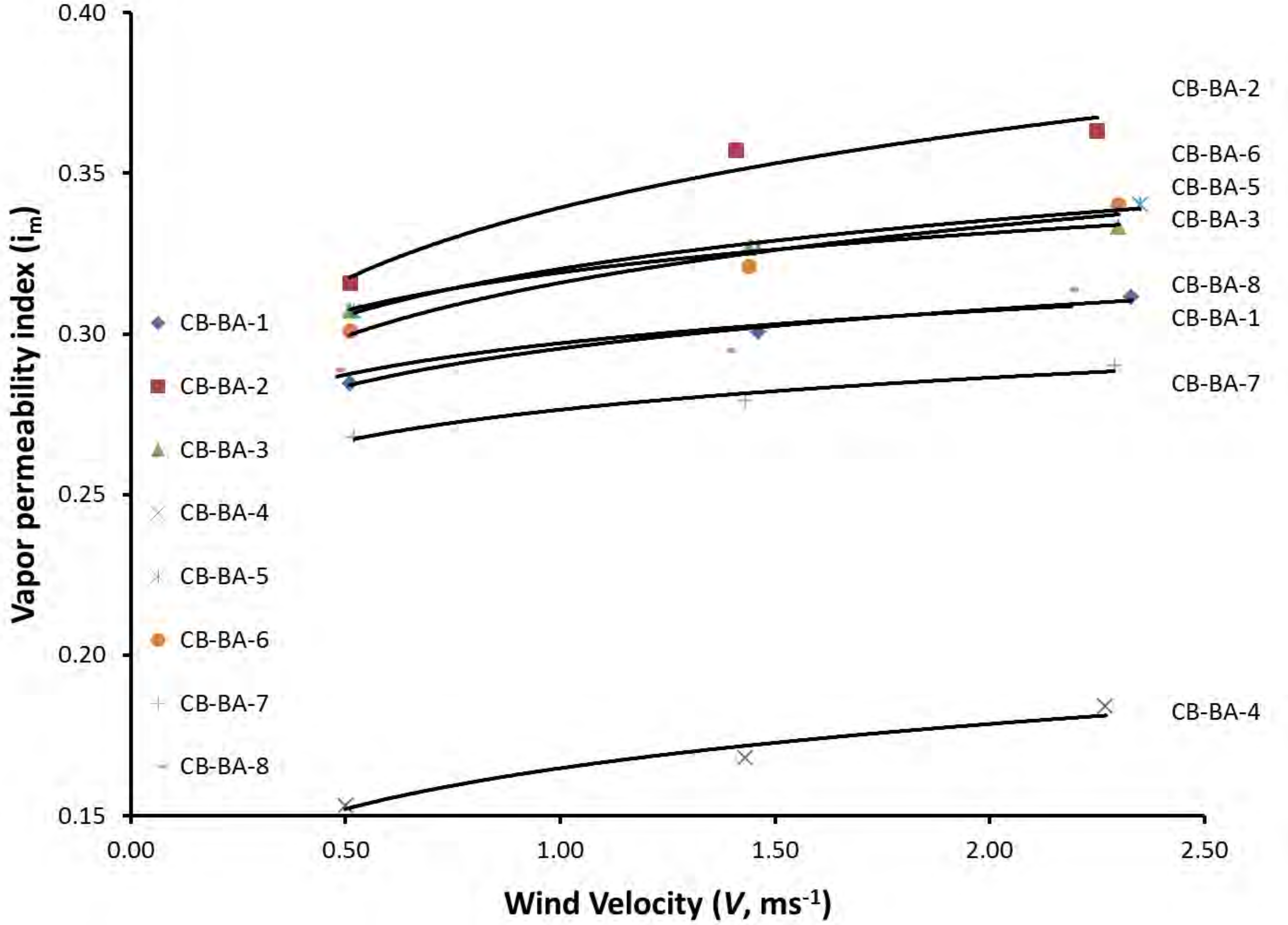


Table 2b. Vapor permeability index (i_m) by wind velocity (*V)* for eight ensembles with body armor and helmet and associated wind velocity coefficient (V^g)

Ensemble	i_m: 1 V: 0.52 ms^{-1}	i_m: 2 V: 1.44 ms^{-1}	i_m: 3 V: 2.30 ms^{-1}	i_mV^g
CB-BA-1	0.28	0.30	0.31	0.06
CB-BA-2	0.17	0.23	0.26	0.10
CB-BA-3	0.16	0.33	0.33	0.06
CB-BA-4	0.15	0.17	0.18	0.12
CB-BA-5	0.31	0.33	0.34	0.07
CB-BA-6	0.30	0.32	0.34	0.08
CB-BA-7	0.27	0.28	0.29	0.05
CB-BA-8	0.29	0.30	0.31	0.05

Figure 3c. Evaporative potential (i_m/clo) by wind velocity (*V)* for eight ensembles with body armor and helmet

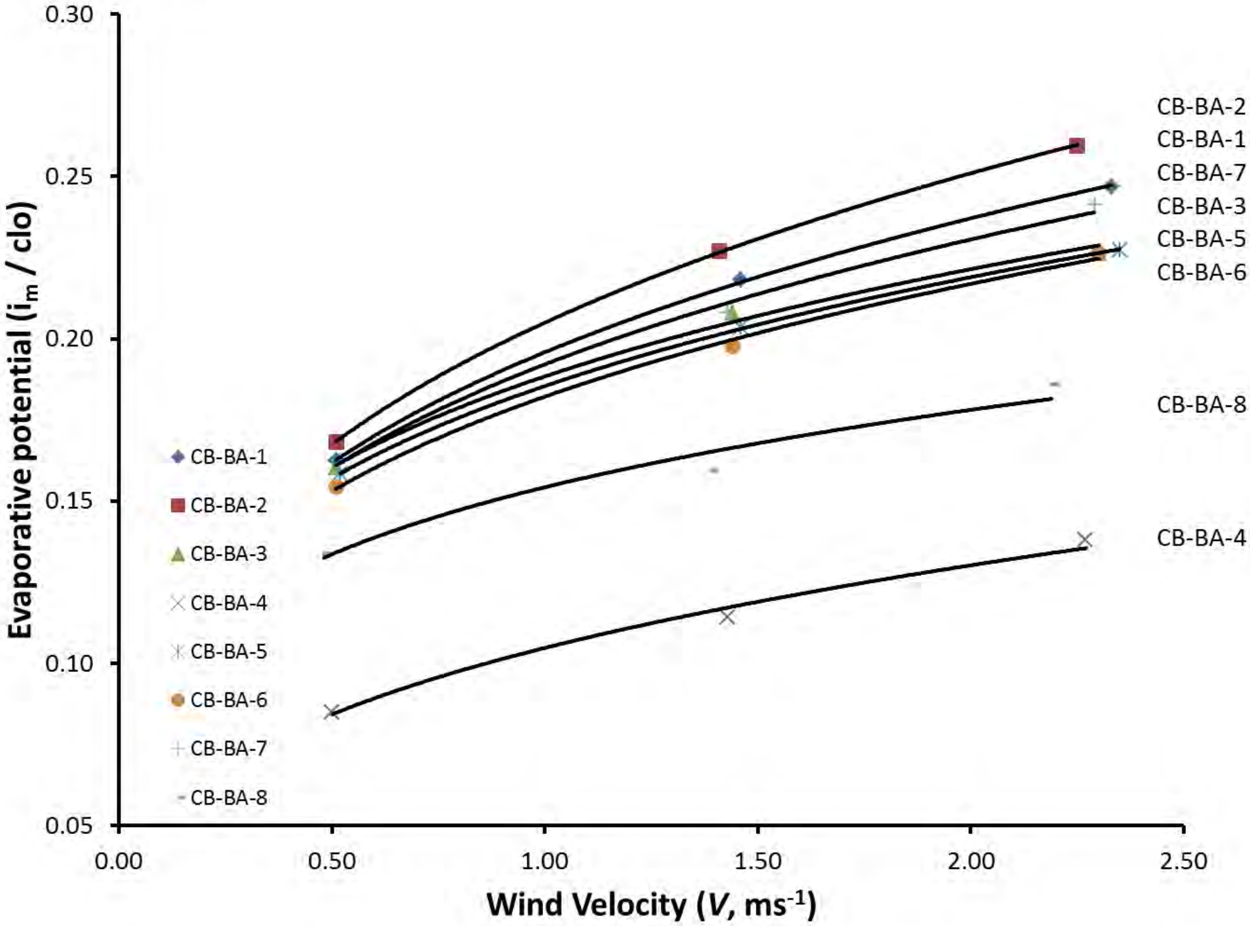


Table 2c. Evaporative potential (i_m/clo) by wind velocity (*V)* for eight ensembles with body armor and helmet and associated wind velocity coefficient (V^g)

Ensemble	i_m/clo: 1 *V*: 0.52 ms^{-1}	i_m/clo: 2 *V*: 1.44 ms^{-1}	i_m/clo: 3 *V*: 2.30 ms^{-1}	i_m/cloV^g
CB-BA-1	0.16	0.22	0.25	0.28
CB-BA-2	0.17	0.23	0.26	0.29
CB-BA-3	0.16	0.21	0.23	0.23
CB-BA-4	0.09	0.11	0.14	0.31
CB-BA-5	0.16	0.20	0.23	0.24
CB-BA-6	0.15	0.20	0.23	0.25
CB-BA-7	0.16	0.21	0.24	0.26
CB-BA-8	0.13	0.16	0.19	0.21

Note: An average of the V for R_{ct} and R_{et} was used to establish this ratio

Figure 4a. Total thermal resistance (I_T, clo) by wind velocity (*V*) for six ensembles with no body armor or helmet

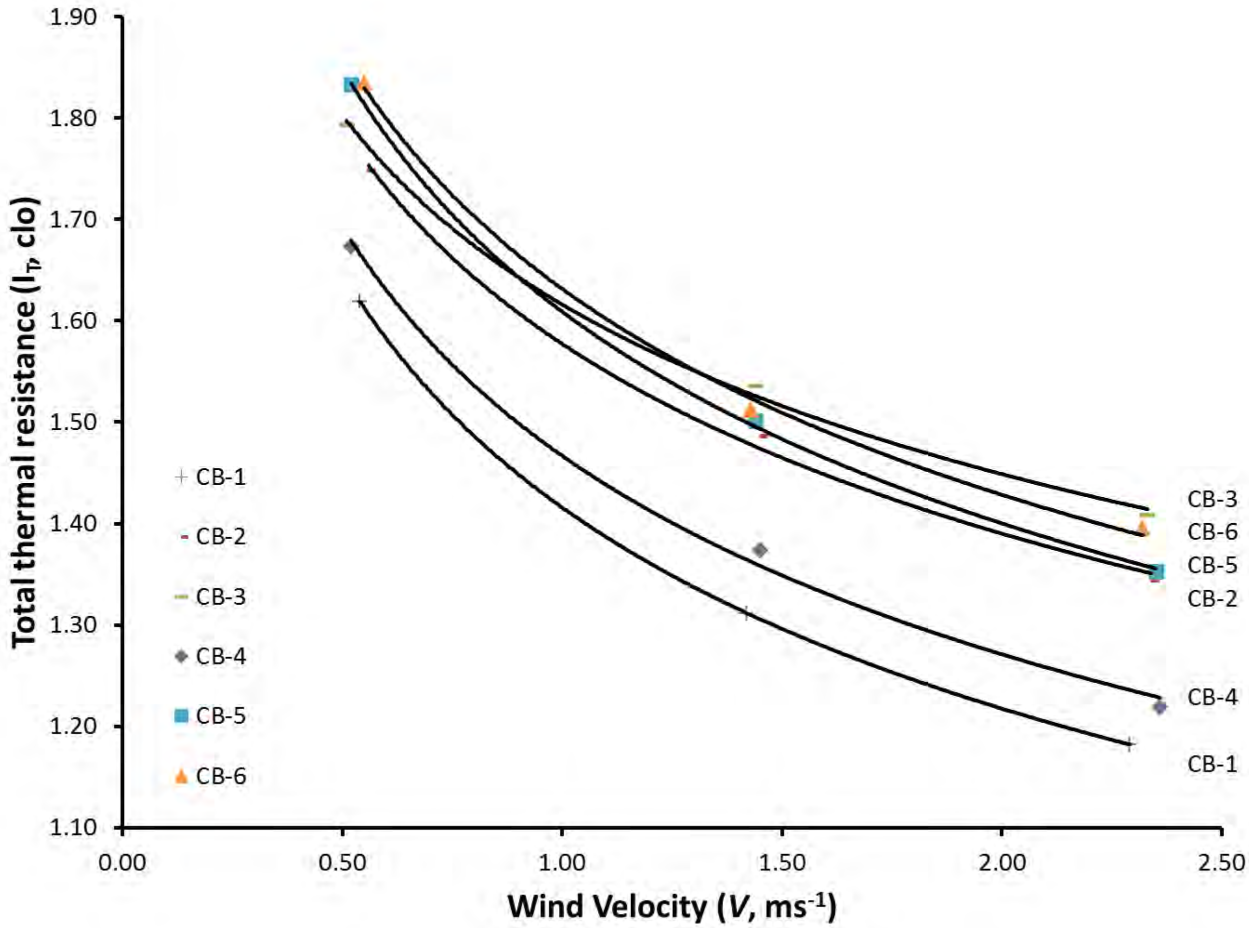


Table 3a. Total thermal resistances (I_T, clo) by wind velocity (*V*) for six ensembles with no body armor or helmet and associated wind velocity coefficient (V^g)

Ensemble	clo: 1 *V*: 0.52 ms^{-1}	clo: 2 *V*: 1.43 ms^{-1}	clo: 3 *V*: 2.31 ms^{-1}	cloV^g
CB- 1	1.62	1.31	1.18	-0.22
CB- 2	1.75	1.49	1.34	-0.18
CB- 3	1.79	1.54	1.41	-0.16
CB- 4	1.67	1.37	1.22	-0.21
CB- 5	1.83	1.50	1.35	-0.20
CB- 6	1.84	1.51	1.40	-0.19

Figure 4b. Vapor permeability index (i_m) by wind velocity (*V*) for six ensembles with no body armor or helmet

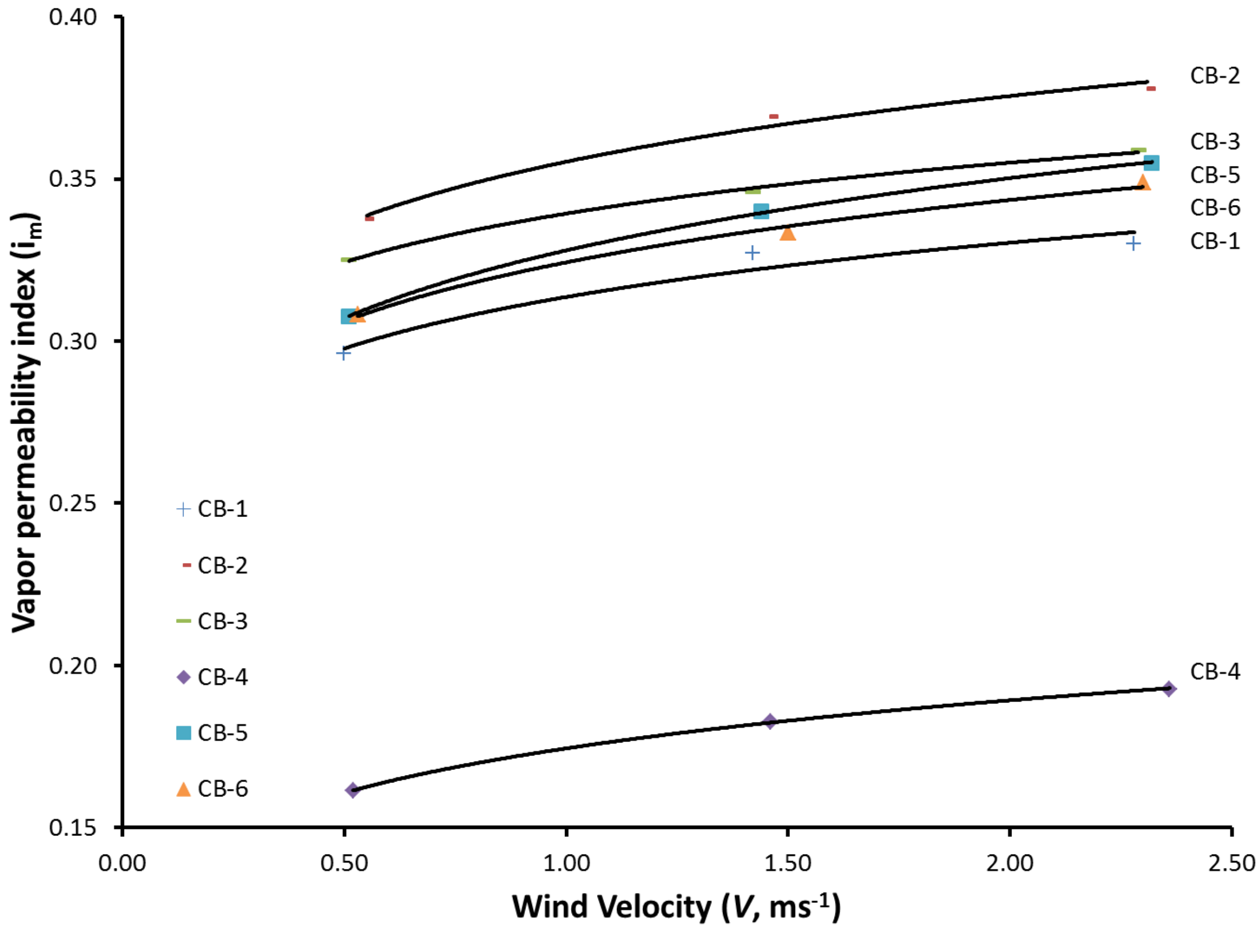


Table 3b. Vapor permeability index (i_m) by wind velocity (*V*) for six ensembles with no body armor or helmet and associated wind velocity coefficient (V^g)

Ensemble	i_m: 1 V: 0.52 ms^{-1}	i_m: 2 V: 1.44 ms^{-1}	i_m: 3 V: 2.30 ms^{-1}	$i_m V^g$
CB- 1	0.30	0.33	0.33	0.08
CB- 2	0.34	0.37	0.38	0.08
CB- 3	0.33	0.35	0.36	0.07
CB- 4	0.16	0.18	0.19	0.12
CB- 5	0.31	0.34	0.36	0.10
CB- 6	0.31	0.33	0.35	0.08

Figure 4c. Evaporative potential (i_m/clo) by wind velocity (*V*) for six ensembles with no body armor or and helmet and associated wind velocity coefficient (V^g)

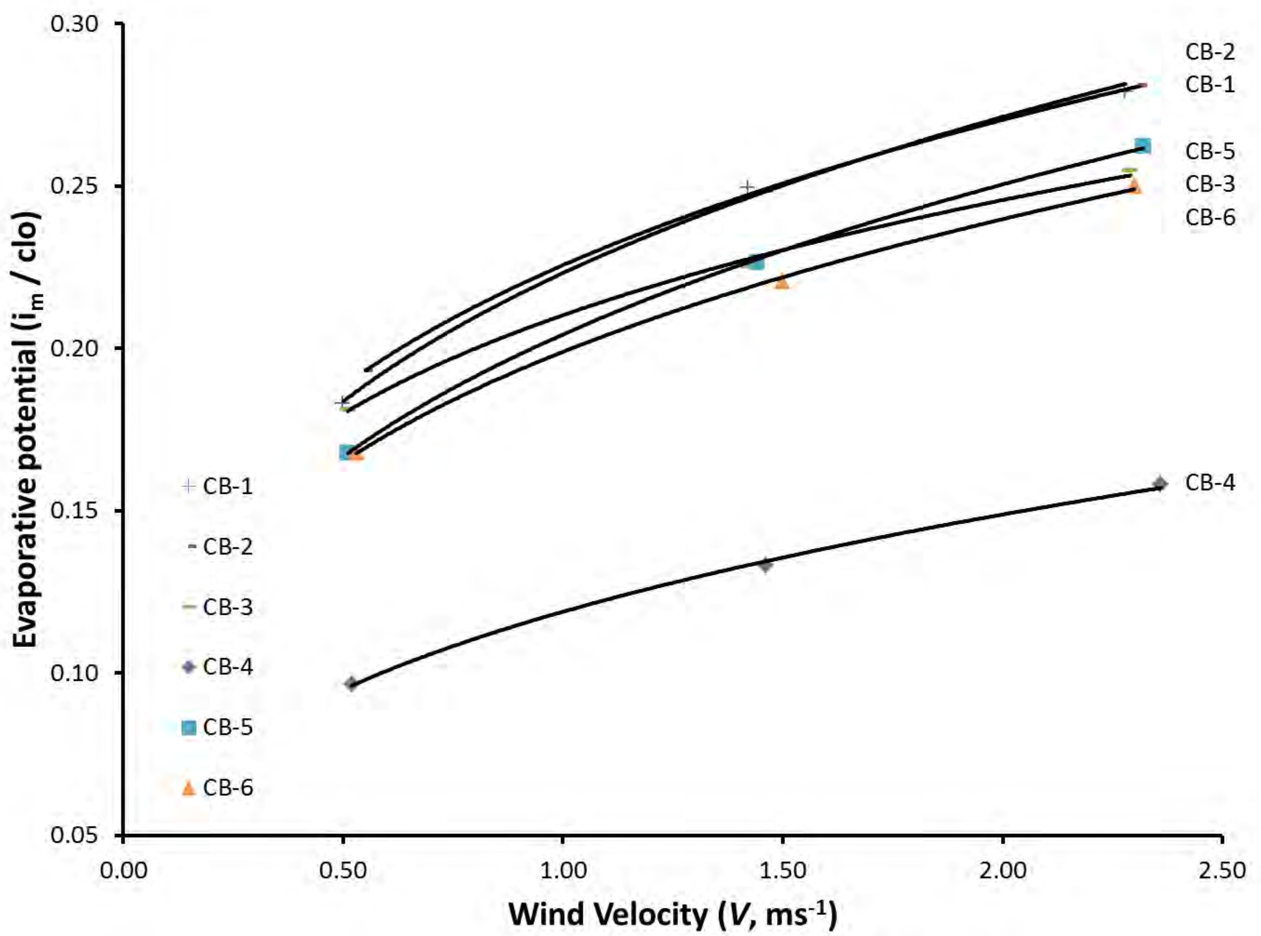


Table 3c. Evaporative potential (i_m/clo) by wind velocity (*V*) for six ensembles with no body armor or and helmet and associated wind velocity coefficient (V^g)

Ensemble	**i_m/clo: 1 V: 0.52 ms^{-1}**	**i_m/clo: 2 V: 1.44 ms^{-1}**	**i_m/clo: 3 V: 2.30 ms^{-1}**	**i_m/cloV^g**
CB- 1	0.18	0.25	0.28	0.28
CB- 2	0.19	0.25	0.28	0.26
CB- 3	0.18	0.23	0.26	0.23
CB- 4	0.10	0.13	0.16	0.32
CB- 5	0.17	0.23	0.26	0.29
CB- 6	0.17	0.22	0.25	0.27

Note: An average of the V for R_{ct} and R_{et} was used to establish this ratio

Estimated Standard Use Values

Typical modeling and simulation efforts use I_T (clo) and i_m values at either the standard 0.4 or 1.0 ms^{-1} *V* [10], therefore these values and the associated V coefficients are provided below for future reference (Table 4a and 4b).

Table 4a. Calculated biophysical characteristics and wind velocity coefficients (V^g) for a wind velocity of 0.4 ms^{-1}

Ensemble	clo	cloV^g	i_m	i_mV^g	i_m/clo	i_m/cloV^g
CB-BA-1	1.83	-0.22	0.28	0.06	0.15	0.28
CB-BA-2	1.98	-0.19	0.31	0.10	0.16	0.29
CB-BA-3	2.00	-0.18	0.30	0.06	0.15	0.23
CB-BA-4	1.89	-0.20	0.15	0.17	0.08	0.31
CB-BA-5	2.02	-0.17	0.30	0.07	0.15	0.24
CB-BA-6	2.03	-0.17	0.29	0.08	0.15	0.25
CB-BA-7	1.74	-0.21	0.26	0.05	0.15	0.26
CB-BA-8	2.23	-0.16	0.28	0.05	0.13	0.21
CB-1	1.73	-0.22	0.29	0.08	0.17	0.28
CB-2	1.86	-0.18	0.33	0.08	0.18	0.26
CB-3	1.87	-0.16	0.32	0.07	0.17	0.23
CB-4	1.77	-0.21	0.16	0.12	0.09	0.32
CB-5	1.93	-0.20	0.30	0.10	0.16	0.29
CB-6	1.95	-0.19	0.30	0.08	0.16	0.27

Table 4b. Calculated biophysical characteristics and wind velocity coefficients (V^g) for a wind velocity of 1.0 ms^{-1}

Ensemble	clo	cloV^g	i_m	i_mV^g	i_m/clo	i_m/cloV^g
CB-BA-1	1.50	-02	0.30	0.06	0.20	0.28
CB-BA-2	1.66	-0.19	0.34	0.10	0.21	0.29
CB-BA-3	1.70	-0.18	0.32	0.06	0.19	0.23
CB-BA-4	1.58	-0.20	0.17	0.12	0.11	0.31
CB-BA-5	1.72	-0.17	0.32	0.07	0.19	0.24
CB-BA-6	1.73	-0.17	0.32	0.08	0.18	0.25
CB-BA-7	1.44	-0.21	0.28	0.05	0.19	0.26
CB-BA-8	1.93	-0.16	0.30	0.05	0.15	0.21
CB-1	1.42	-0.22	0.31	0.08	0.22	0.28
CB-2	1.58	-0.18	0.36	0.08	0.23	0.26
CB-3	1.62	-0.16	0.34	0.07	0.21	0.23
CB-4	1.47	-0.21	0.17	0.12	0.12	0.32
CB-5	1.61	-0.20	0.33	0.10	0.20	0.29
CB-6	1.63	-0.19	0.32	0.08	0.20	0.27

Addition of Body Armor

Of significant interest to the military is the increased thermal burden associated with wearing body armor [11-12]. During CBRN operations this is especially significant given the water vapor impermeable nature of current body armor. The relative percent change with adding body armor and helmets to ensemble numbers 1 through 6 (CB to CB-BA) can be seen in Tables 5a and 5b at calculated measures of 0.4 and 1.0 ms^{-1} V. As the wind effects differ across these ensembles, it is important to recognize the relative impacts from body armor expected for each at both near-still air (0.4 ms^{-1}) and typical air movement (1.0 ms^{-1}).

Table 5a. Percent change from adding body armor and helmet to ensembles 1-6 on total thermal resistance (I_T, clo), vapor permeability index (i_m), and evaporative potential (i_m/clo) at 0.4 ms^{-1}

Ensemble comparison	**clo**	**i_m**	**i_m/clo**
CB-1 → CB-BA-1	6%	-6%	-12%
CB-2 → CB-BA-2	5%	-5%	-9%
CB-3 → CB-BA-3	5%	-6%	-10%
CB-4 → CB-BA-4	7%	-6%	-12%
CB-5 → CB-BA-5	7%	-2%	-9%
CB-6 → CB-BA-6	6%	-3%	-8%
Average change with added body armor and helmet	6%	-4%	-10%

Table 5b. Percent change from adding body armor and helmet to ensembles 1-6 on total thermal resistance (I_T, clo), vapor permeability index (i_m), and evaporative potential (i_m/clo) at 1.0 ms^{-1}

Ensemble comparison	**clo**	**i_m**	**i_m/clo**
CB-1 → CB-BA-1	6%	-4%	-12%
CB-2 → CB-BA-2	6%	-6%	-12%
CB-3 → CB-BA-3	7%	-5%	-11%
CB-4 → CB-BA-4	7%	-5%	-11%
CB-5 → CB-BA-5	4%	0%	-5%
CB-6 → CB-BA-6	4%	-2%	-7%
Average change with added body armor and helmet	6%	-4%	-10%

DISCUSSION

This study compared the biophysical characteristics of 14 ensembles using standardized methods. Quantitative assessment of the biophysical characteristics of clothing using thermal sweating manikins provides the basis for mathematical prediction of thermal strain [13]. In a practical sense, quantifying the biophysical characteristics of the ensembles and ranking them relative to different wind velocity conditions provides a reasonable assessment of the clothing thermal characteristics. However, since air movement significantly influences these values, a ranking of how these ensembles perform relative to increases in wind velocity is of interest. Figures 5 and 6 rank each ensemble based on its respective clo and i_m/clo with increases in wind velocity from 0.4 to 1.0 ms^{-1}. Table 6 ranks each ensemble's magnitude of change from the standard measures at 0.4 and 1.0 ms^{-1}. From this ranking we can see that at different conditions of air movement there is better performance potential for some of the ensembles, e.g., CB-BA-3 i_m/clo increases by 19% going from 0.4 to 1.0 ms^{-1} and improves its relative ranking from 7th to 9th (Figure 6).

Figure 5. Ranking of ensemble total insulation (clo) with increases in wind velocity of 0.4 to 1.0 ms^{-1}

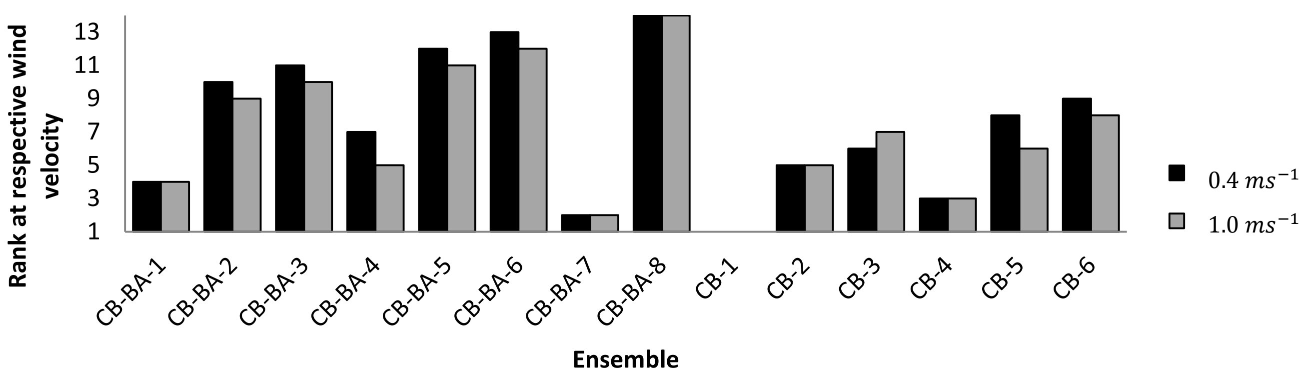


Figure 6. Ranking of ensemble evaporative potential (i_m/clo) with increases in wind velocity of 0.4 to 1.0 ms^{-1}

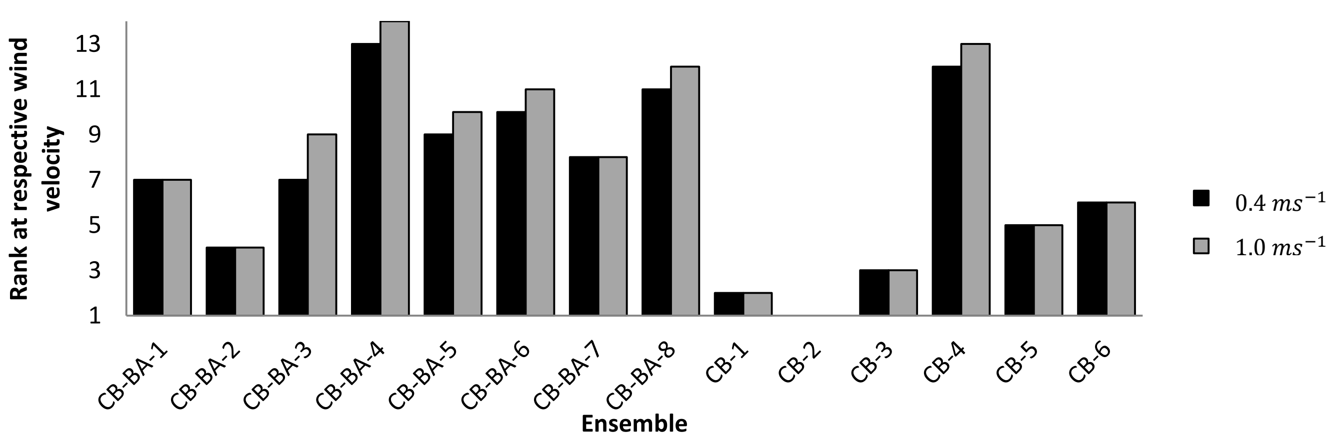


Table 6. Ranking of ensemble potential for reduced thermal burden by clo and i_m/clo and percent change with increases in wind velocity of 0.4 to 1.0 ms^{-1}

Ensemble	clo rank lowest-highest		clo % change	i_m/clo rank highest-lowest		i_m/clo % change
	0.4 ms^{-1}	1.0 ms^{-1}	Δ	0.4 ms^{-1}	1.0 ms^{-1}	Δ
CB-BA-1	4	4	-22%	7	7	22%
CB-BA-2	10	9	-19%	4	4	23%
CB-BA-3	11	10	-18%	7	9	19%
CB-BA-4	7	5	-20%	13	14	25%
CB-BA-5	12	11	-17%	9	10	19%
CB-BA-6	13	12	-17%	10	11	20%
CB-BA-7	2	2	-21%	8	8	21%
CB-BA-8	14	14	-16%	11	12	17%
CB-1	1	1	-22%	2	2	23%
CB-2	5	5	-18%	1	1	21%
CB-3	6	7	-16%	3	3	19%
CB-4	3	3	-21%	12	13	26%
CB-5	8	6	-20%	5	5	24%
CB-6	9	8	-19%	6	6	22%

This work reflects a quantitative assessment of clothing ensembles at a system-level (full ensemble). While flat plate testing of two-dimensional textile swatches has value, it is difficult to translate these results to the whole-human [5]. The total resistance of any ensemble consists of three main elements: air gap (R_{gap}), clothing textile (R_{cl}), and boundary layer (R_{bl}); where the total resistance can be seen as: $Resistance = R_{gap} + R_{cl} + R_{bl}$. While the sweating thermal manikin measures these as system-level, recent work suggests that these elements can be estimated or measured at a component level and therefore estimates can be derived for the system as a whole [14-17]. Collectively, biophysical testing, modeling, and human research complete the arc of fully assessing thermal properties of clothing. From an economic standpoint, the methodological approach described here is among the most cost effective means of gaining a quantitative biophysical assessment of the whole system. However, if a component-level method can be developed and validated, the time and resources needed to make a quantitative assessment could be dramatically reduced.

From an operational perspective, there are a number of countermeasures that can be used to mitigate the risk of heat strain, e.g., work-rest cycling and the use of personal cooling systems. Managing work-rest has significant benefit, e.g., stop in a favorable microclimate (e.g., shade) to rest and reduce metabolic heat produced and to rest and open PPE for evaporative cooling. While wearing protective clothing, microclimate cooling systems have significant benefits [18]. Extensive work has been conducted in assessing the biophysical properties of active cooling suits using manikin and modeling methods [19-20] as well as human assessments of active cooling systems [21-26]. Inherent logistical issues exist with active systems (e.g., power, weight) as well as duration of system operations (e.g., battery life) versus activity

demands of the wearer; therefore, an ideal approach is passive cooling [27-28]. Passive systems enable cooling with reduced logistical and power constraints. For activities where individuals wear impermeable EOD suits, active cooling may be appropriate as wearers typically wear suits for relatively short durations, e.g., < 1 h; while for CBRN operations or first responder activities passive systems are ideal, as activity durations are typically prolonged, e.g., > 4 h. Whether active or passive, these cooling systems become more critical in hot, humid environments where evaporative cooling is ineffective.

This study assessed the thermal burden imposed by military-specific CBRN protective ensembles. This information can be used to assess the balance between CBRN protection and thermal burden. The challenge of balancing protection with the need to minimize encapsulation is also be seen in law enforcement [29-30], first responders [31], health hazard assessment and clinical responders such as medical teams in West Africa in response to Ebola Virus outbreaks [32-33]. The biophysical properties of clothing and individual equipment alter the human's thermodynamic interaction with the environment, and are of significant importance for understanding and optimizing clothing to mitigate thermal burden.

CONCLUSIONS

The work outlined in this report represents scientific assessments of the biophysical characteristics across a range of wind velocities for 14 different CBRN ensembles. From these biophysical assessments clear differences can be in the various ensembles and imposed thermal burden. These data can be used as part of a larger scale analysis to assess the tradeoff between the amounts of CBRN protection provided by each ensemble and the potential for reducing thermal burden.

REFERENCES

1. Medical Surveillance Monthly Report (MSMR). Armed Forces Health Surveillance Center, 21(3), pp 10-13, March 2014, accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a598313.pdf
2. Tharion WJ, Potter AW, Duhamel CM, Karis AJ, Buller MJ, & Hoyt RW. Real-time physiological monitoring while encapsulated in personal protective equipment. *Journal of Sport and Human Performance*, *1*(4), 2013.
3. ASTM International. F1291-10 Standard test method for measuring the thermal insulation of clothing using a heated manikin. 2010. http://www.astm.org/Standards/F1291.htm
4. ASTM International. F2370-10 Standard test method for measuring the evaporative resistance of clothing using a sweating manikin. 2010. http://www.astm.org/Standards/F2370.htm
5. Xu X, Rioux TP, & Potter AW. Fabric thermal resistance and ensemble thermal resistances are two different concepts. *Journal of Occupational and Environmental Hygiene*, *11*(11), D187-D188, 2014.
6. Gagge AP, Burton AC, & Bazett HC. A practical system of units for the description of the heat exchange of man with his environment. *Science*, 94:428-30, 1941.
7. Woodcock AH. Moisture transfer in textile systems, Part I. *Textile Research Journal, 32*(8), 628-633, 1962.
8. Potter AW, Walsh M, & Gonzalez JA. Explosive ordnance disposal (EOD) ensembles: Biophysical characteristics and predicted work times with and without chemical protection and active cooling systems. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T15-5, 2015, ADA#618081 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a618081.pdf
9. Woodcock AH. Moisture permeability index - A new index for describing evaporative heat transfer through fabric systems. Quartermaster Research and Engineering Command, Natick, MA 01702 USA, Technical Report (TR-EP-149), 1961.
10. Potter AW, Gonzalez JA, Karis AJ, Rioux TP, Blanchard LA, & Xu X. Impact of estimating thermal manikin derived wind velocity coefficients on physiological modeling. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T14-7, 2014, ADA#607972 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a607972.pdf
11. Potter AW, Karis AJ, & Gonzalez JA. Biophysical characterization and predicted human thermal responses to US Army body armor protection levels (BAPL). U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T13-5, 2013, ADA#585406, accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a585406.pdf

12. Potter AW, Gonzalez JA, Karis AJ, & Xu X. Biophysical assessment and predicted thermophysiologic effects of body armor. *PLoS One*, 2015. DOI: 10.1371/journal.pone.0132698

13. O'Brien C, Blanchard LA, Cadarette BS, Endrusick TL, Xu X, Berglund LG, Sawka MN, & Hoyt RW. Methods of evaluating protective clothing relative to heat and cold stress: thermal manikin, biomedical modeling, and human testing. *Journal of Occupational and Environmental Hygiene, 8*(10), 588-599, 2011.

14. Kim Y, Lee C, Li P, Corner BD, & Paquette S. Investigation of Air Gaps Entrapped in Protective Clothing System. *Fire and Materials, 26*(3), 121-126, 2002.

15. Song G. Clothing air gap layers and thermal protective performance in single layer garment. *Journal of Industrial Textiles, 36*(3), 193-205, 2007.

16. Ding D, Tang T, Song G, & McDonald A. Characterizing the performance of a single-layer fabric system through a heat and mass transfer model-Part I: Heat and mass transfer model. *Textile Research Journal*, 2010.

17. Ding D, Tang T, Song G, & McDonald A. Characterizing the performance of a single-layer fabric system through a heat and mass transfer model–Part II: Thermal and evaporative resistances. *Textile Research Journal,* 2011.

18. Cadarette BS, Levine L, Staab JE, Kolka MA, Correa M, Whipple M, & Sawka MN. Heat strain imposed by toxic agent protective systems. *Aviation, Space, and Environmental Medicine, 72*(1), 32-37, 2001.

19. Xu X, Endrusick T, Laprise B, Santee W, & Kolka M. Efficiency of liquid cooling garments: prediction and manikin measurement. *Aviation, Space, and Environmental Medicine, 77*(6), 644-648, 2006.

20. McCullough EA, & Eckels S. Evaluation of personal cooling systems for soldiers. In Proceedings 13th International Conference on Environmental Ergonomics, 200-204, 2009.

21. Cadarette BC, Latzka WA, Levine L, & Sawka MN. A physiological evaluation of a prototype air-vest microclimate cooling system. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T14-91, 1991, ADA#262083, accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a262083.pdf

22. Cadarette BS, Levine L, Kolka MA, Proulx GN, Correa MM, & Sawka MN. Heat strain reduction by ice-based and vapor compression liquid cooling systems with a toxic agent protective uniform. *Aviation, Space and Environmental Medicine, 73*(7), 665-672, 2002.

23. Cheuvront SN, Kolka MA, Cadarette BS, Montain SJ, & Sawka MN. Efficacy of intermittent, regional microclimate cooling. *Journal of Applied Physiology, 94*(5), 1841-1848, 2003.

24. Cadarette BS, Levine L, Staab JE, Kolka MA, Correa MM, Whipple M, & Sawka MN. Upper body cooling during exercise-heat stress wearing the improved toxicological agent protective system for HAZMAT operations. *AIHA Journal, 64*(4), 510-515, 2003.

25. Cadarette BS, Cheuvront SN, Kolka MA, Stephenson LA, Montain SJ, & Sawka MN. Intermittent microclimate cooling during exercise-heat stress in US army chemical protective clothing. *Ergonomics, 49*(2), 209-219, 2006.

26. Chinevere TD, Cadarette BS, Goodman DA, Ely BR, Cheuvront SN, & Sawka MN. Efficacy of body ventilation system for reducing strain in warm and hot climates. *European Journal of Applied Physiology, 103*(3), 307-314, 2008.

27. Berglund L, & Hoyt R. U.S. Patent No. 8,495,767. Washington, DC: U.S. Patent and Trademark Office, 2013

28. Gonzalez RR, Breckenridge JR, Levell CA, Kolka MA, & Pandolf KB. Efficacy of heat exchange by use of a wettable cover over chemical protective garments. *ASTM Special Technical Publication*, (900), 515-534, 1986.

29. Yokota M, Karis AJ, & Tharion WJ. Thermal-work strain in law enforcement personnel during chemical, biological, radiological, and nuclear (CBRN) training. *International Journal of Occupational and Environmental Health*, *20*(2), 126-133, 2014.

30. Yokota M, Karis AJ, Goetz VC, & Tharion WJ. Evaluation of physiological strain in law enforcement personnel wearing protective clothing and equipment. *The FASEB Journal*, *27*, 1201-9, 2013.

31. Buller MJ, Tharion WJ, Karis AJ, Santee WR, Mullen SP, & Hoyt RW. *Real Time Physiological Monitoring of Encapsulated Team Members of the 1st Civil Support Team–Weapons of Mass Destruction (CST-WMD)*. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report T08-01, 2007, ADA#473188 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a473188.pdf

32. Roberts I, & Perner A. Ebola virus disease: clinical care and patient-centered research. *The Lancet*, *384*(9959), 2001-2002, 2014.

33. Chertow DS, Kleine C, Edwards JK, Scaini R, Giuliani R, & Sprecher A. Ebola virus disease in West Africa—clinical manifestations and management. *New England Journal of Medicine*, *371*(22), 2054-2057, 2014.

APPENDIX A.

Table 1a. Ensemble configuration symbols and detailed descriptions

<table>
<tr><th>Ensemble symbol</th><th>Suit</th><th>Mask</th><th>Gloves</th><th>Footwear</th><th>Undergarments</th><th>Additional equipment</th><th>Body armor</th><th>Helmet</th><th>Figure</th></tr>
<tr><td>CB-BA-1</td><td>Prototype 1</td><td rowspan="5">M50 w/ hood</td><td rowspan="14">JB1GU</td><td rowspan="14">IFS Socks, Std. Socks Std. boots</td><td rowspan="14">100% cotton briefs, 100% polyester wicking t-shirt</td><td rowspan="14">Mask Carrier, Neck Dam</td><td rowspan="8">Cyre</td><td rowspan="8">MICH</td><td>1A</td></tr>
<tr><td>CB-BA-2</td><td>Prototype 2</td><td>2A</td></tr>
<tr><td>CB-BA-3</td><td>Prototype 3</td><td>3A</td></tr>
<tr><td>CB-BA-4</td><td>USCG AP PPE</td><td>4A</td></tr>
<tr><td>CB-BA-5</td><td>JSLIST</td><td>5A</td></tr>
<tr><td>CB-BA-6</td><td>JSLIST</td><td>M50 no hood</td><td>5A</td></tr>
<tr><td>CB-BA-7</td><td>FRACU</td><td>M50 w/ hood</td><td>N/A</td></tr>
<tr><td>CB-BA-8</td><td>JSLIST over FRACU</td><td>M50 no hood</td><td>5A</td></tr>
<tr><td>CB-1</td><td>Prototype 1</td><td rowspan="5">M50 w/ hood</td><td rowspan="6">None</td><td rowspan="6">None</td><td>1A</td></tr>
<tr><td>CB-2</td><td>Prototype 2</td><td>2A</td></tr>
<tr><td>CB-3</td><td>Prototype 3</td><td>3A</td></tr>
<tr><td>CB-4</td><td>USCG AP PPE</td><td>4A</td></tr>
<tr><td>CB-5</td><td>JSLIST</td><td>5A</td></tr>
<tr><td>CB-6</td><td>JSLIST</td><td>M50 no hood</td><td>5A</td></tr>
</table>

Figure 1A. Thermal manikin wearing the CB-BA-1 ensemble

*CB-1 is identical to the above except that body armor and helmet are removed

Figure 2A. Thermal manikin wearing the CB-BA-2 ensemble

*CB-2 is identical to the above except that body armor and helmet are removed

Figure 3A. Thermal manikin wearing the CB-BA-3 ensemble

*CB-3 is identical to the above except that body armor and helmet are removed

Figure 4A. Thermal manikin wearing the CB-BA-4 ensemble

*CB-4 is identical to the above except that body armor and helmet are removed

Figure 5A. Thermal manikin wearing the CB-BA-5, CB-BA-6, and CB-BA-8 ensembles

*CB-BA-5 includes chemical protective hood
**CB-BA-6 is without the chemical protective hood
***CB-BA-8 includes FRACU under this suit; without the chemical protective hood
*CB-5 is identical to the above except that body armor and helmet are removed
*CB-6 is identical to the above except that body armor and helmet are removed